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13. ABSTRACT (Maximum 200 words)

The tunable HTS program goals are to develop a process, method, or device to tune high-temperature superconductor (HTS) resonant circuits. The process for tuning should preserve the low-loss nature of the superconducting resonant circuits and be compatible with the operating environment of packaged HTS RF circuitry. Although we were originally developing three technologies to perform this tuning, we have downselected to the two that offer the greatest potential for high Q operation, the half-HTS MEMS variable capacitor and the continuously variable inductor. The target application is for this technology is SIGINT applications in the 400 MHz to 3000 MHz frequency band, with potential applications in areas from 20 MHz to 20 GHz.

We reached a significant milestone with the demonstration of the continuously variable inductors. In this demonstration we achieved a 23% tuning range, with better than 1 part in 10,000 resettability, and a Q of over 10,000. These are significant achievements in the area of tunable filters.

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Final Report Covering 09/10/1998 to 12/31/2001

1.) List of Papers Submitted or Published

No publications have resulted from the work on this program.

2.) Scientific Personnel

The personnel who have worked on this project in this period include: Dr. Joseph E. Mancusi [MCNC], Dr. Mark W. Roberson [MCNC], Dr. Phil Deane [MCNC], Dr. Ken Williams [MCNC], Dr. David Dausch [MCNC], Dr. W. Devereux (Dev) Palmer [MCNC], Mr. Richard LaBennett [MCNC], Mr. David Vellenga [MCNC], Dr. Sarah Hurlston-Vargas [MCNC], Dr. Brett Guenther [MCNC], Mr. Alan Huffman [MCNC], Dr. Balam A. Willemsen [STI], Dr. Eric Prophet [STI], Dr. Robert Hammond [STI], Mr. Kaspar Mossman [STI], Mr. David A. Koester [Cronos], Dr. Ramaswamy (Ramu) Mahadevan [Cronos], Mr. Ed Hill [Cronos], Dr. Vijay Dhuler [Cronos], and Ms. Karen Markus [Cronos]. These people are from three organizations supporting this contract, MCNC, Cronos Integrated Microsystems, Inc. [an MCNC spin-off and now a wholly-owned subsidiary of JDS Uniphase] both of Research Triangle Park, North Carolina, and Superconductor Technologies Incorporated [STI] of Santa Barbara, California.

3.) Report of Inventions

There are a few inventions to report by title: SRT-461 Wide Frequency Range, High Resolution Frequency Error Measurement, SRT-471 Means of Extending Oscillating Range for Resonator, SRT-464 Improved HTS Filter Actuators, SRT-482 Microwave Tunable Filter with Multiple Frequency Ranges

4.) Scientific Progress and Accomplishments

This program has advanced the state of the art in tunable electronic filters. The main goal of the work was to develop approaches best suited to making tunable filters which had the key advantages of more conventional fixed frequency high temperature superconductor (HTS) filters. These filters are characterized by extremely low loss (in effect, four orders of magnitude less surface resistance) which allows for complex, highly defined frequency profiles to be built in microstrip filters retaining low insertion loss.

The main areas of progress surround the advances and first example of operation of the continuously variable inductor and measured results from two actuation mechanisms other than the baseline magnetic field actuation approach. The goals were achieved on this program and are world best performance for tunable devices, including a tuning range of 23% in a device with an unloaded Q of 10,000.

The half-HTS work has progressed in a refinement phase to increase the reliability, yield, and Q of the fabricated devices. We have concluded the development of the all-metal MEMS variable capacitor since the possibility of achieving Q's greater than 10,000 with these devices is limited. Both the half-HTS variable capacitor and the continuously variable inductor approaches offer significantly better performance.

Program Goals

The tunable HTS program goals are to develop a process, method, or device to tune high-temperature superconductor (HTS) resonant circuits. The process for tuning should preserve the low-loss nature of the superconducting resonant circuits and be compatible with the operating environment of packaged HTS RF circuitry. The three basic approaches

mentioned above are examples of this approach and, of course, have their own advantages and disadvantages as approaches to achieving tuning. The target application is for this technology is SIGINT applications in the 400 MHz to 3000 MHz frequency band, with potential applications in areas from 20 MHz to 20 GHz.

The basic elements of a tunable cryogenic HTS front end filter system are: 1.) a fixed bandpass filter (BPF), 2.) a cryogenic low noise amplifier (cryo-LNA), and 3.) a tunable HTS/ MEMS bandpass resonator (BPR). These elements will be housed together in a closed-cycle refrigerator housing with appropriate RF feed lines and electronic controls. The standard STI rack mount system, one of which is shown in the accompanying picture, uses U.S. standard household electricity delivered through a 120 Volt wall outlet.

In addition, for the continuously variable inductor approach, we established the following performance goals for demonstration in calendar year 2000:

- Unloaded Q = 10,000

- Center Frequency = 775 MHz
- Filter 3 dB Bandpass = 1.0 - 1.5 MHz
- Tunability = +/- 2.5%
- Resettability = 1 part in 10,000
- Settling time = 50 ms

We achieved all of these goals except the settling time during this performance period.

The measured results from this program, summarized for tunability figure of merit K in Figure 2, are much better than the results achieved with ferroelectrics, ferromagnetics, ferrites, or solid-state approaches such as varactor diodes.
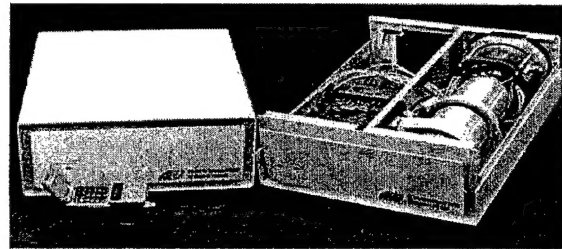

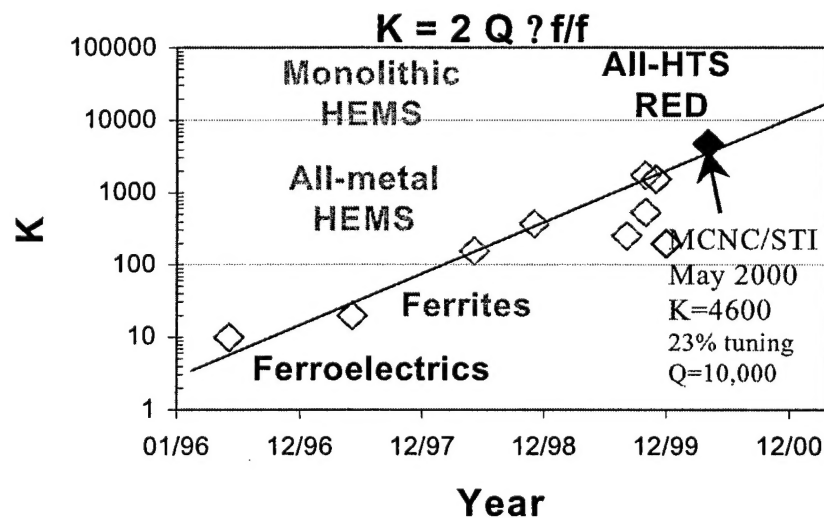Figure 1. STI's commercial HTS filter enclosure.

Figure 2. Progress in tuning frequency agile filters using tunability figure of merit, K.

MCNC

All-metal MEMS variable capacitor

The work on the all-metal MEMS variable capacitor has ended and transitioned over to solving fabrication issues for the half-HTS MEMS variable capacitor. The all-metal MEMS variable capacitor does work as projected, but cannot sustain losses low enough to achieve unloaded Q's above 10,000. Thus, one of the unique features of tunable HTS filters is compromised by the use of upper and lower normal metal capacitor plates in the RF section of the filter. No follow-on work is planned on this structure.

The goal of the metal variable capacitor work is to develop a MEMS-based variable capacitor for integration with a fixed response HTS resonator circuit specifically designed to incorporate the tuning it provides. The variable capacitors are designed and fabricated with low loss materials for cryogenic operation. Although we make every effort to preserve Q (reduce loss), there are inherent limitations to the Q achievable with the approach of using metal variable capacitors that limits the ultimate unloaded Q of the tunable resonant circuit. However, the unloaded Q may be adequate for many applications and this work provides a pathway for monolithic integration of MEMS and HTS. The measured performance of the all-metal MEMS variable capacitors reported herein is the best performance to date of any similar device, indicating 7.6% tuning range and an unloaded Q of greater than 2020. The main achievements have been in redesigning the device structure and fabrication process to achieve better RF performance, wider tuning range, lower operating voltage, and reduce hysteretic behavior. These efforts will be discussed in this section.

Strategy

Develop electrostatically actuated variable capacitor based on bimorph flap using non-HTS materials that are develop process and materials that are compatible with HTS circuit fabrication. Establish an evolutionary path for technology transfer to producing variable capacitors with metal top plates on HTS substrates (the half-HTS approach).

Design and Fabrication

The basic MEMS variable capacitor structure that has proven most successful is a metal bimorph flap. The two metals used to make a bimorph are chosen for stability and in general will have different thermal expansion coefficients. When deposited, there is stress at the interface between the two metals. Since the materials have different thermal expansion coefficients, they are more stressed as the temperature is raised or lowered from the deposition temperature. At temperatures above the deposition temperature, this stress is released by changes in the metal interface caused by grain growth and interdiffusion. Below the deposition temperature, and certainly at room temperature and below (the operating temperatures for these HTS devices are -196 C), these interface and interdiffusion changes occur slowly, so that the only stress relief is through the curling of the flap upon release.

This methodology was used initially in the development of the bimorph flap and results were given in the previous interim report. Several issues were raised at that time about important operating characteristics of these variable capacitors and they were addressed in a redesign carried out during our work in calendar year 1999. The variable capacitors structures were redesigned to improve the tuning range, reduce the tuning voltage, improve the Q (reduce RF losses), reduce hysteresis, and improve the yield of fabricated devices. These considerations compelled us to increase the lower electrode to approximately 5 microns thick, to reduce the dielectric layer thickness, to change the anchor design, and to reduce the amount of dielectric in the RF path. All results discussed here involve Au/Al bimorph variable capacitors were fabricated on a quartz substrate.

Lower Electrode

The lower electrode thickness was larger than can be planarized for fabrication of subsequent layers over this electrode. Thus, we were required to trench the electrode into the quartz

substrate and polish the surface. Eventually, the choice was made to use the dielectric to planarize the trenched layer and this worked fairly well, but working out these details caused several months of delay. This issue continues to compromise device yield.

Anchor Designs

Early designs to assist in reducing initial pull-down voltage resulted in devices that were too compliant, i.e., they moved too readily under an applied force. Since this force can be either electromagnetic or mechanical, there are several possible problems with the stability of these variable devices. These include microphonic sensitivity and the possibility of RF power induced phase distortion. In addition, small changes in layer thickness will cause large changes in device operating performance, resulting in poor device uniformity. We have redesigned these devices to use the most solid basic geometry (the cantilever) with modifications of the area of DC pull down electrode coverage and changes in the anchor.

Improve Q

The high Q of HTS filters is the most desirable and useful property. Thus, every effort should be focused toward maintaining a high Q in operation. An all-metal variable capacitor is naturally hybrid, or fabricated on a separate substrate from the rest of the HTS filter. [This was discussed in the previous interim report covering 1998.] Since this normal metal filter

element is in the circuit, its losses will dominate the filter Q and great care should be taken to limit this degradation. Several aspects of loss were addressed in this area, including reducing the length of bond wires to connect the metal variable capacitor into the RF circuit, modifying the RF leads, eliminating the coupling of RF power into the DC network by improving the bias tees, and by reducing the RF signal path length in the flap. These changes had a modest impact on the circuit Q.

Hysteresis And Stiction

Stiction in MEMS devices is caused by charge trapping in dielectric and by surface charge effects. These trapped charges help to shield the EM field, thus changing the voltage-capacitance curve and resulting in hysteresis. We took steps to eliminate the dielectric in signal path areas that are likely to cause hysteresis. This did reduce, but not eliminate, the hysteresis. In addition, we are using self-assembled monolayers of alkanethiolates to make exposed dielectric surfaces hydrophobic, thus eliminating the charge trapping on the treated surfaces. Using a self-assembled monolayer approach, the metallophilic head group attaches to the Au (111) surface, and hydrocarbon tails provide hydrophobicity (20-30 Å thick). This has worked very well and reduced hysteresis to a very minor level. It has also eliminated the need for critical point drying, a very labor-intensive step in the post-processing sequence.

Half-HTS MEMS variable capacitor

A large amount of the work on the half-HTS MEMS variable capacitor has been mainly to increase the reliability of the fabrication of the half-HTS devices and to change the design to improve the unloaded Q.

While the all-metal variable capacitor has shown promise in operation as a variable capacitor, there are several issues that make its application to tunable high-Q filters difficult. First, there are limitations on the Q that is achievable in a hybrid HTS filter all-metal variable capacitor device. The limitations are caused by the wire bonds connecting the device to the HTS filter and the loss within the

variable capacitor itself. Thus, the tenability figure of merit, or K, is limited as well. These problems are fundamental, meaning that there is no way to avoid or work around them. For instance, wire or ribbon bonds are the only practical way of connecting the all-metal variable capacitor. Some reduction of losses in the variable capacitor itself could occur if there were thicker metal in the RF active areas, but this change would cause many other problems including reduced compliance, higher operating voltages, more difficulty isolating DC and RF circuits, and processing complexities. Thus, we have explored making

variable capacitors with the lower electrode formed in the HTS filter circuit and made from HTS material, the half-HTS device. These devices will have unloaded Q's several times higher than the all-metal variable capacitors increasing their application for tunable filters.

Using an existing geometric device designs, STI has been able to fabricate these devices very quickly, with measured results occurring only four weeks from the initial design and mask layout. The efforts that have resulted in promising measurements and a baseline approach for fabrication. Development is needed in several of the underlying technology areas including the device design and hysteresis reduction. These issues continue to receive the attention of the research team and as many of them are detailed under the previous section, they will not be repeated here.

Continuously Variable Inductor

The baseline approach for the continuously variable inductor is to suspend a high temperature superconductor (HTS) reaction plate above an HTS resonant element by means of a fiber. The fiber is attached at the ends and the fiber provides a low torsional resistance movement for the structure. This concept has been patented by Dr. Richard Eden and we have referred to it interchangably as the Richard Eden device or the continuously variable inductor (CVI).
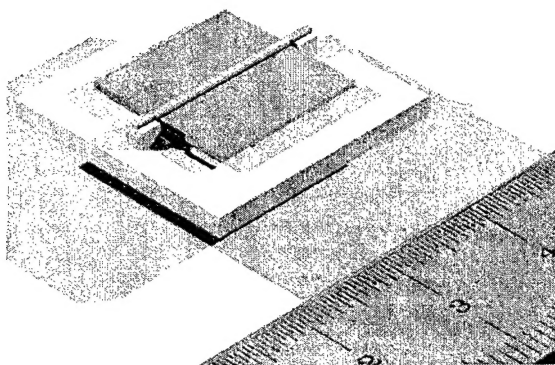

Figure 3. Conceptual drawing of the continuously variable inductor.

The continuously variable inductor approach uses a low torsion suspension holding a movable HTS plate above a substrate as shown in Figure 3. The major benefit to this approach is that all the surfaces carrying RF power are fabricated from HTS (other than wire bonds that connect the lower substrate to the external connectors). Thus, the continuously variable inductor has the possibility for both large variations in tuning (greater than 50% bandwidth), and large unloaded Q factors (greater than 10,000 over the whole band). A generalized version of this approach would use any method for controlling the relative spacing of two HTS plates and results are shown herein for two alternative approaches using a voice coil actuator and a piezoelectric actuator.

Development of the CVI

The first work on the continuously variable inductor began in June 1999 and is focused on the demonstration of the technology. The initial design is for tunability over the range of 800 MHz to 750 MHz corresponding to a gap of 100 microns to 400 microns with a sense resonator at 1.4 GHz and a tightly coupled bandpass filter. We expect to be able to achieve closed loop tuning in 50 milliseconds with resettability of 1 part in 10,000 in frequency. We have outlined critical tasks in several key areas: filter design, frequency measurement, packaging and assembly, materials compatibility, device driver, device controller, and testing and validation. The methodology for tuning the plate is to use external drive coils producing a magnetic field, as shown in Figure 4. The magnetic field produced by these coils is repelled by the HTS material on the top plate causing the plate motion. This is our baseline approach for achieving tuning.
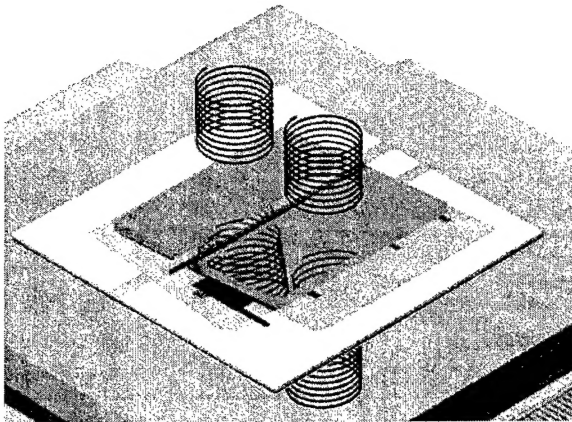
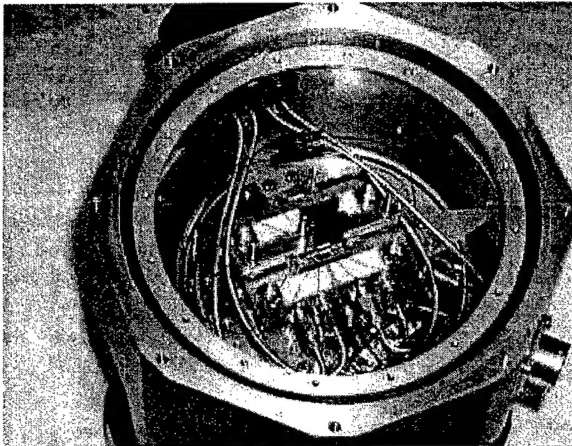*Figure 4. Actuation mechanism for continuously variable inductor.*

Figure 5. Physical implementation of baseline approach.

The physical implementation of our baseline approach is shown in the picture of Figure 5. The device in Figure 5 is shown in a liquid nitrogen dewar for testing. We established the following performance goals for demonstration in calendar year 2000:

- Unloaded Q = 10,000
- Center Frequency = 775 MHz
- Filter 3 dB Bandpass = 1.0 - 1.5 MHz
- Tunability = +/- 2.5%
- Resettability = 1 part in 10,000

- Settling time = 50 ms

and achieved all of these goals save settling time during the period of performance for this report. The measured performance of this oals were achieved on this program and are world best performance for tunable devices, including a tuning range of 23% in a device with an unloaded Q of 10,000.

The CVI can be driven by coils, as shown in Figures 4 and 5, or by a voice coil or piezoelectric driver. In order to compare performance, we have put together alternative drivers for the top HTS plate. With a piezoelectric lever arm bimorph, we achieved 3% tuning using voltages up to 500 Volts for actuation. The measured results are shown in Figure 6. Piezoelectric drivers such as these have several disadvantages including high driving voltages and low force to mass ratios indicating progress in this area probably would not lead to increased performance over the baseline approach. Figure 7 shows the measured tuning response for a voice coil actuator attached to the device. Figure 8 shows the measured results for our baseline approach of Figure 4, a CVI with external magnetic drive coils. The measured results in Figures 7 and 8 were not calibrated and no inference should be made regarding the absolute scale of S11/S21.
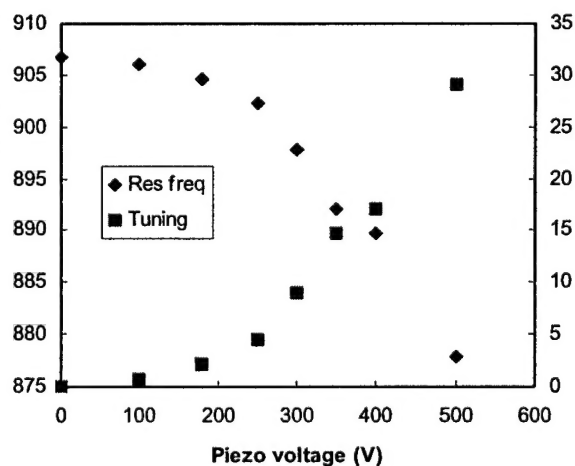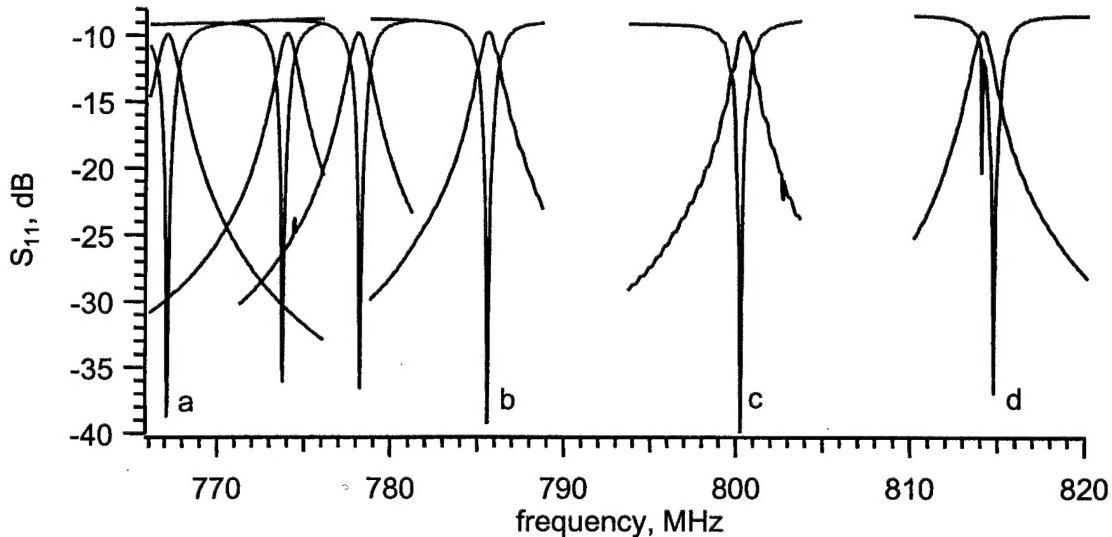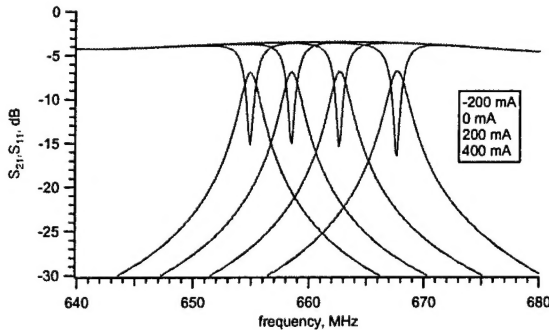

Figure 6. Measured tuning response for piezoelectrically driven CVI.

Figure 7. Measured tuning response for voice coil driven CVI.

28 April 2000, MCNC
HTS Resonator S_{11} and S_{21} versus external coil drive current:

Figure 8. Measured frequency response of tunable HTS filter using baseline approach with external drive coils.

Monitoring Sense Resonance Frequency

To achieve <1:10,000 resolution requires accurate measurement of a quantity directly related to the frequency of the resonator. This can be achieved by measuring either the physical position of the plate, the resonant frequency of the resonator coil, or the resonant frequency of a reference coil that has a one-to-one correspondence to the resonant coil. Our approach uses frequency measurement of a reference coil - a highly accurate technique. We will monitor the frequency of the filter using a feedback signal that is electrically isolated from the filter signal of interest so as not to introduce losses in the desired filter signal and, therefore, lower the Q. MCNC has designed a frequency-locking scheme using frequency and phase/frequency detectors that provides real time accuracy of better than 0.003%. This concept

combines digital and RF linear and non-linear elements.

Assembly

Using optics fixturing, we have assembled several units using silicon die of the same size as the HTS pieces. We purchased fiber materials (ceramic, metal,carbon) of various sizes with a range of tensile strength & stiffness (elastic modulus) properties. We have performed pull and creep tests of the fibers, measured the alignment precision, and adhesion.

Control Electronics And Common Control Architecture

The control interface is designed to adjust the frequency of the filter peak and to provide diagnostic information about the filter performance. We have created software control panels for the control circuit, which allow both direct control of the frequency and remote control of the circuit. The remote control is important because it allows this design to run seamlessly with external validation programs. The control architecture baseline process uses feedback through frequency determination. The basic units are the oscillator, the frequency locked loop (FLL), and the control algorithm. The controller uses a common architecture design, meaning that the interface is not specifically tied to the tunable filter technology specifically, but is general enough to be used for both variable capacitor and variable inductor designs. For these uses the designed for virtual front panel or IEEE-488 or binary control To develop the control algorithms, MCNC is using a PC frame for the first year demonstration. The test bed allows for rapid prototyping changes in ADC/DAC inputs and in control algorithms

Frequency Agile Test Station

The initial integration of hardware and software for the frequency agile test station was completed in CY2000 and used for filter testing. The goal of the testing and validation procedure is to provide realistic signal scenarios that the frequency agile filter is likely to see in fielding, and to provide a text-based script to control the filters and retrieve data while in test.

The frequency agile test station implements the test procedure, schematically shown in Figure 9, that is enabled by having the common control architecture. During testing, a frequency hopper controller receives information from a PC about what test is being run. This is sent over a text messaging system. In turn, this controller sets up the test by running the signal generators and noise power sources, sending protocols to the front end controller on the frequency agile filter, and receiving signals, for instance on a power meter. In this fashion, a suite of signal scenarios can be run without the intervention of an operator and realistic filter performance specifications can be measured.
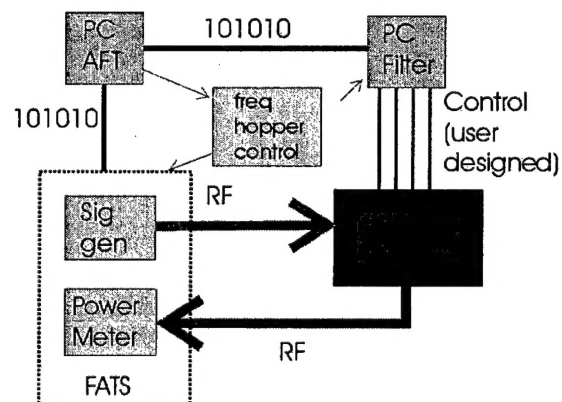

Figure 9. Process of controlling the frequency agile filters during testing.

In general, the noise, jamming, and signal sources are all frequency agile. These noise sources include signal components for co-site simulation, tone/woodpecker jamming, and broad-band jammers. These sources will be flexible enough for any fielded communications mock-up and include AM, FM, FM, and programmable digital modulation schemes as well as combinations thereof. We plan on developing the system controller to be independent of the type of frequency agile filter that is being tested. Figure 10 shows a picture of the frequency agile test station as set up for a test. The aluminum canister holds one of the frequency agile filters developed in this program.

Figure 10. Picture of the frequency agile test station.
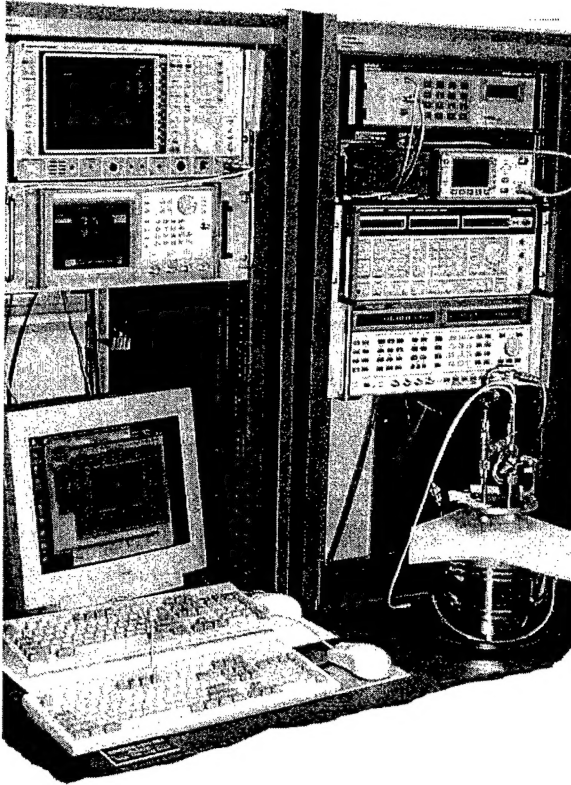
5.) Technology Transfer

In April of 1999, Cronos Integrated Microsystems Incorporated was spun-off as a for-profit wholly owned subsidiary of MCNC, a not-for-profit company, to commercialize MEMS devices and products. In December 1999, they closed on first-round private financing of approximately $8 million. In April 2000, Cronos Integrated Microsystems Incorporated was purchased in a stock transaction by JDS Uniphase Corporation (NASD: JDSU), a publicly traded company. They plan to develop new MEMS optical switching technologies as well as work with commercial and military customers to develop and fabricate commercial MEMS-based products.

Superconductor Technologies Incorporated is a publicly-traded company developing products using high-temperature superconductors. Information can be obtained from their web site (www.suptech.com) and company publications.